

Constraining Neutrino Mass from Neutrinoless Double Beta Decay

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We re-analyze the compatibility of the claimed observation of neutrinoless double beta decay ($0\nu\beta\beta$) in ^{76}Ge with the new limits on the half-life of ^{136}Xe from EXO-200 and KamLAND-Zen. Including recent calculations of the nuclear matrix elements (NMEs), we show that while the claim in ^{76}Ge is still compatible with the individual limits from ^{136}Xe , it is inconsistent with the KamLAND-Zen+EXO-200 combined limit for all but one NME calculations. After imposing the most stringent upper limit on the sum of light neutrino masses from Planck, we find that the canonical light neutrino contribution cannot satisfy the claimed $0\nu\beta\beta$ signature or saturate the current limit, irrespective of the NME uncertainties. However, inclusion of the heavy neutrino contributions, arising naturally in TeV-scale Left-Right symmetric models, can saturate the current limit of $0\nu\beta\beta$. In a type-II seesaw framework, this imposes a lower limit on the lightest neutrino mass. Depending on the mass hierarchy, we obtain this limit to be in the range of 0.07 - 4 meV for a typical choice of the right-handed (RH) gauge boson and RH neutrino masses relevant for their collider searches. Using the $0\nu\beta\beta$ bounds, we also derive correlated constraints in the RH sector, complimentary to those from the LHC.

Introduction – The discovery of neutrino oscillations, and hence, non-zero neutrino masses and mixing implies physics beyond the Standard Model (SM). Some of the unresolved issues are (i) whether neutrinos are Majorana or Dirac particles, (ii) their absolute mass scale, and (iii) their mass hierarchy. Neutrinoless double beta decay ($0\nu\beta\beta$) [1], if observed, would imply lepton number violation (LNV) and Majorana nature of neutrinos [2], and could possibly shed light on the other issues.

Experimental studies of the $0\nu\beta\beta$ process: $(A, Z) \rightarrow (A, Z+2) + 2e^-$ have been conducted on several nuclei, and to date, there has been only one claimed observation in ^{76}Ge with half-life $T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$ yr at 68% CL [3]. Several ongoing experiments have design sensitivities to test this claim. Recently, the KamLAND-Zen (KLZ) experiment using ^{136}Xe obtained the limit $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr at 90% CL [4]. After combining with the EXO-200 (EXO) results, $T_{1/2}^{0\nu} > 1.6 \times 10^{25}$ yr [5], they derived the limit $T_{1/2}^{0\nu} > 3.4 \times 10^{25}$ yr at 90% CL [4], and disfavored the claim in [3] at $> 97.5\%$ CL, using recent calculations of the nuclear matrix elements (NMEs).

On the other hand, the Planck results in conjunction with other cosmological data have put a stringent upper limit on the sum of light neutrino masses: $\sum m_\nu < 0.23$ eV at 95% CL [6], which rules out most of the quasi-degenerate region of the light neutrino mass spectrum. This has important consequences for the canonical interpretation of $0\nu\beta\beta$ via light neutrino exchange [7].

In this paper we study the implications of these recent results on various aspects of the $0\nu\beta\beta$ phenomenology, namely, we (i) re-analyze the compatibility of the KamLAND-Zen and EXO-200 limits with the claimed

observation [3], including the uncertainties due to several updated NME calculations; (ii) quantify whether the standard light neutrino prediction for $0\nu\beta\beta$ can satisfy the claimed observation or saturate the current limit, while being consistent with the stringent neutrino mass constraints from cosmology; and (iii) investigate whether a heavy neutrino contribution naturally arising in low scale Left-Right symmetric models (LRSM), accessible at the LHC, can saturate the $0\nu\beta\beta$ limit.

Light Neutrino Contribution– For $0\nu\beta\beta$ mediated by the light Majorana neutrinos, the half-life is given by

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} |\mathcal{M}_\nu|^2 \left| \frac{m_{ee}^\nu}{m_e} \right|^2, \quad (1)$$

where $G_{0\nu}$, \mathcal{M}_ν and m_e are the the phase space factor, the NME, and the electron mass respectively. Here $m_{ee}^\nu = \sum_i U_{ei}^2 m_i$ is the effective mass, where U is the PMNS mixing matrix diagonalizing the light neutrino mass matrix with eigenvalues m_i ($i = 1, 2, 3$). Using the standard parametrization for U , we obtain (with $c_{ij} \equiv \cos \theta_{ij}$, $s_{ij} \equiv \sin \theta_{ij}$)

$$m_{ee}^\nu = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3 s_{13}^2 e^{2i\alpha_3}. \quad (2)$$

To test the compatibility between the claim in [3] and the null results in [4, 5], it is useful to study the correlation between their half-lives (see also [8]) using Eq. (1):

$$T_{1/2}^{0\nu}(^{136}\text{Xe}) = (3.61_{-0.83}^{+1.18} \times 10^{24} \text{ yr}) \left| \frac{\mathcal{M}_{0\nu}(^{76}\text{Ge})}{\mathcal{M}_{0\nu}(^{136}\text{Xe})} \right|^2 \quad (3)$$

where we have used the recently re-evaluated phase space factors [9] for the axial-vector coupling constant $g_A = 1.25$. We take the claimed value for $T_{1/2}^{0\nu}(^{76}\text{Ge})$ [3] at

90% CL (assuming Gaussian errors). An experimental limit on $T_{1/2}^{0\nu}(^{136}\text{Xe})$ larger than the predicted value from Eq. (3) will rule out the positive claim of [3]. Using various updated NME calculations [10–16], we show in Table I the predicted range of $T_{1/2}^{0\nu}(^{136}\text{Xe})$ at 90% CL. We find that it is still compatible with the individual limits from KLZ and EXO for some of the NMEs, but inconsistent with their combined limit in [4] for all of the NME values, except the one given in [16]. The reason is the very small NME for ^{136}Xe in [16], which can be attributed to the differences in pairing structure in the neutron mean fields, thus leading to a small overlap in the initial and final mean fields.

NME			$T_{1/2}^{0\nu}(^{136}\text{Xe})$
Method	$\mathcal{M}_{0\nu}(^{76}\text{Ge})$	$\mathcal{M}_{0\nu}(^{136}\text{Xe})$	[10^{25} yr]
EDF(U) [10]	4.60	4.20	0.33 - 0.57
ISM(U) [11]	2.81	2.19	0.46 - 0.79
IBM-2 [12]	5.42	3.33	0.74 - 1.27
pnQRPA(U) [13]	5.18	3.16	0.75 - 1.29
SRQRPA-B [14]	5.82	3.36	0.84 - 1.44
SRQRPA-A [14]	4.75	2.29	1.20 - 2.06
QRPA-B [15]	5.571	2.460	1.43 - 2.46
QRPA-A [15]	5.157	2.177	1.56 - 2.69
SkM-HFB-QRPA [16]	5.09	1.89	2.02 - 3.47

TABLE I. Predictions for $T_{1/2}^{0\nu}(^{136}\text{Xe})$ at 90% CL corresponding to the claimed $0\nu\beta\beta$ observation in ^{76}Ge [3] for the latest results of different NME calculations [10–16].

The maximum and minimum values of the NMEs given in Table I correspond to the following 90% CL ranges: $m_{ee}^\nu < (0.11 - 0.24)$ eV for KamLAND-Zen+EXO (KLZ+EXO), and $m_{ee}^\nu = (0.21 - 0.58)$ eV for the claim in [3]. Note that these ranges should not be used directly to test the compatibility between [4] and [3], since the limiting values of m_{ee}^ν for ^{136}Xe and ^{76}Ge do not necessarily correspond to the same NME calculation. The best way is to compare the half-lives, as shown in Table I, which are independent of the effective neutrino mass and hence oscillation parameter uncertainties.

To compare the experimental results with the canonical light neutrino contribution given by Eq. (1), we show in Fig. 1 the predicted half-lives for ^{76}Ge and ^{136}Xe as a function of the lightest neutrino mass for normal and inverted mass orderings, including the hierarchical and quasi-degenerate (QD) regimes. We have varied the oscillation parameters in their 3σ range [17], the CP phases from 0 to π , and included the NME uncertainties from Table I (light shaded regions). Note that the predicted regions of half-life for normal hierarchy (NH) and inverted hierarchy (IH) almost overlap due to the NME uncertainties. However, for a given set of NMEs (e.g., those of [14] taken here for illustration), we recover the standard pic-

ture with the two (dark shaded) regions well-separated. The green (solid) horizontal lines in the left panel of Fig. 1 correspond to the 90% CL claim value of [3] (KK), and the brown (dashed) horizontal line for the lower limit set by the Heidelberg-Moscow collaboration [18] (HM). The orange (solid) and brown (dashed) horizontal lines in the right panel represent the 90% CL lower limits for ^{136}Xe from KLZ and combined KLZ+EXO [4] respectively. The solid vertical line shows the 95% CL limit, $\sum m_\nu < 0.23$ eV (Planck1), derived from the Planck+WMAP low-multipole polarization+high resolution CMB+baryon acoustic oscillation (BAO) data and assuming a standard ΛCDM model of cosmology, whereas the dashed vertical line shows the limit without the BAO data set: $\sum m_\nu < 0.66$ eV (Planck2) [6].

The current constraints on $0\nu\beta\beta$ (including the claim) can be saturated by the canonical contribution only in the QD regime with $m_1 \simeq m_2 \simeq m_3 \equiv m_0 \gtrsim 0.1$ eV. As it is evident from Fig. 1, this possibility is excluded, regardless of the NME uncertainties, if we take the most stringent upper limit from cosmology which for QD neutrinos gives $m_0 < 0.077$ eV. For other cosmological data sets, only a very narrow allowed mass window remains.

Heavy Neutrino Contribution– The heavy right-handed (RH) neutrinos, introduced in the type-I seesaw [19] models, if sufficiently light (≤ 10 TeV), can give a significant contribution to $0\nu\beta\beta$ [20] provided their mixing with the active neutrinos is sizable. However, this requires fine-tuning and/or cancellation [21]. A more natural way to obtain appreciable heavy neutrino contributions to the $0\nu\beta\beta$ amplitude arises in the TeV scale LRSM [22] via RH currents [23, 24]. Such models also lead to other high and low-energy phenomena and could for instance be directly probed at the LHC through the same-sign dilepton signal [25].

The LRSM includes heavy neutrinos as part of the $SU(2)_R$ doublet and restores parity at high energies [22]. This naturally leads to small neutrino masses through either type-I seesaw via the RH neutrinos [19] or type-II seesaw via $SU(2)$ triplet scalars [26] or both [27]. The corresponding Lagrangian is given by

$$\begin{aligned} \mathcal{L}_Y = & f_\nu \bar{L}_L \Phi L_R + \tilde{f}_\nu \bar{L}_L \tilde{\Phi} L_R + f_L L_L^\dagger C i \sigma_2 \Delta_L L_L \\ & + f_R L_R^\dagger C i \sigma_2 \Delta_R L_R + \text{h.c.} \end{aligned} \quad (4)$$

Here C is the charge conjugation operator and σ_2 the second Pauli Matrix, $L_{L(R)}$ denotes the lepton doublet, Φ the SM Higgs doublet, $\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$, and $\Delta_{L(R)}$ the scalar triplet belonging to $SU(2)_{L(R)}$. The light neutrino mass matrix in the seesaw approximation is $M_\nu \simeq m_L - m_D^\dagger M_R^{-1} m_D$, where $m_D = f_\nu v$, $m_L = f_L v_L$, $M_R = f_R v_R$, and v , $v_{L(R)}$ are the vacuum expectation values of doublet and triplet Higgs fields: $\langle \Phi \rangle = v$, $\langle \Delta_{L(R)} \rangle = v_{L(R)}$. The heavy neutrino masses $\sim M_R$ are related to the RH gauge boson mass $M_{W_R} = g v_R$.

There are several diagrams leading to double beta decay in LRSM (see [1] and references therein). In this work

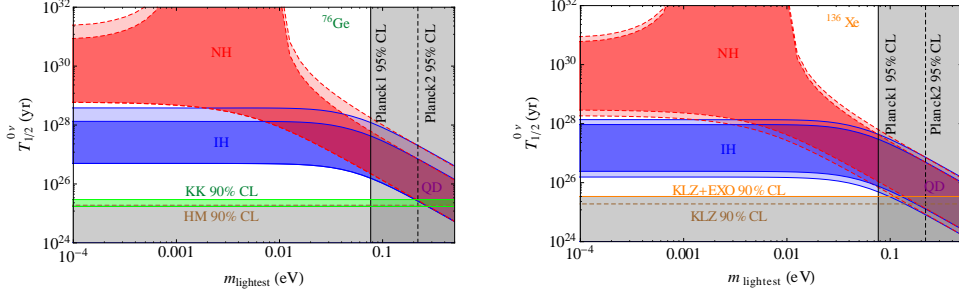


FIG. 1. The predicted half-life of $0\nu\beta\beta$ in ^{76}Ge and ^{136}Xe due to light neutrino exchange. The light shaded regions include the uncertainties due to all the NMEs listed in Table I, whereas the dark shaded regions correspond to the NMEs in [14]. The gray regions are excluded from $0\nu\beta\beta$ and Planck results (see text for details).

we consider the appealing case of type-II dominance [23]. A general analysis involving the Dirac term m_D is not very illuminating and will be given elsewhere. Also, the scalar triplet contribution is expected to be small due to constraints from lepton flavor violation, which typically require $M_N/M_\Delta \lesssim 0.1$ [23]. Hence, we focus only on the diagram with purely RH currents, mediated by the heavy neutrinos which adds coherently to the purely left-handed light neutrino contribution discussed earlier:

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} |\mathcal{M}_\nu|^2 \left| \frac{m_{ee}^{(\nu+N)}}{m_e} \right|^2, \quad (5)$$

where $\left| m_{ee}^{(\nu+N)} \right|^2 = |m_{ee}^\nu|^2 + |m_{ee}^N|^2$, with m_{ee}^ν given by Eq. (2) and m_{ee}^N is the heavy neutrino effective mass:

$$m_{ee}^N = \langle p^2 \rangle \frac{M_{W_L}^4}{M_{W_R}^4} \sum_j \frac{V_{ej}^2}{M_j}. \quad (6)$$

Here $\langle p^2 \rangle = -m_e m_p \mathcal{M}_N / \mathcal{M}_\nu$ denotes the virtuality of the exchanged neutrino, m_p is the mass of the proton and \mathcal{M}_N is the NME corresponding to the RH neutrino exchange. Using the values for \mathcal{M}_ν and \mathcal{M}_N from [14], we get $\langle p^2 \rangle = -(157 - 185 \text{ MeV})^2$ for ^{136}Xe and $-(153 - 184 \text{ MeV})^2$ for ^{76}Ge . The unitary matrix V in Eq. (6) diagonalizes M_R with mass eigenvalues M_j . We further assume the discrete LR symmetry to be parity, under which $f_L = f_R$ and $U = V$. Our conclusions remain unchanged for the other possibility viz. charge conjugation: $f_L = f_R^*$ and $U = V^*$.

In the type-II limit, $M_\nu \simeq m_L = (v_L/v_R)M_R$ and $m_i \propto M_i$. Hence, for the normal ordering we have $M_1 < M_2 \ll M_3$ as well, and the RH neutrino masses can be expressed in terms of the heaviest one as $M_1/M_3 = m_1/m_3$, $M_2/M_3 = m_2/m_3$. Then

$$m_{ee}^N|_{\text{nor}} = \frac{C_N}{M_3} \left(\frac{m_3}{m_1} c_{12}^2 c_{13}^2 + \frac{m_3}{m_2} s_{12}^2 c_{13}^2 e^{2i\alpha_2} + s_{13}^2 e^{2i\alpha_3} \right),$$

where $C_N = \langle p^2 \rangle M_{W_L}^4 / M_{W_R}^4$. For inverted ordering, M_2

will be the largest, and hence

$$m_{ee}^N|_{\text{inv}} = \frac{C_N}{M_2} \left(\frac{m_2}{m_1} c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{2i\alpha_2} + \frac{m_2}{m_3} s_{13}^2 e^{2i\alpha_3} \right).$$

In Fig. 2, we show the half-life predictions for ^{76}Ge and ^{136}Xe using Eq. (5), and including the light and heavy neutrino NME ranges given in [14] (corresponding to $g_A = 1.25$). Here we have chosen $M_{W_R} = 3 \text{ TeV}$ and the heaviest neutrino mass, $M_{N_3} = 1 \text{ TeV}$, keeping in mind the current LHC exclusion limits [28] and its future accessible range. Note that for this choice of M_{N_3} , and for the range of the lightest neutrino mass shown in Fig. 2, the lightest RH neutrino mass is $M_{N_1} > 490 \text{ MeV}$, which justifies the validity of Eq. (6). Several important conclusions can be drawn from this illustrative plot: (i) the purely RH contribution via exchange of heavy neutrinos, when added to the standard light neutrino contribution, can saturate the current experimental limit (or satisfy the claim) even for hierarchical neutrinos; (ii) for the heavy neutrino contribution saturating the bound on $T_{1/2}^{0\nu}$, there exists an absolute lower bound on the lightest neutrino mass both for orderings: (2 - 4) meV for NH and (0.07 - 0.2) meV for IH. The range is due to the combined effect of the NME uncertainties and the 3σ range of the oscillation parameters used here; (iii) the KK claim can be reached for the lightest neutrino mass in the range of (1 - 3) meV for NH and (0.03 - 0.1) meV for IH. These values are well within the most stringent Planck limit of 77 meV; iv) for the heavy neutrino contribution, the compatibility between the KK claim and KLZ+EXO bound can be examined using Eq. (3), with the NMEs for light neutrinos replaced by those for heavy neutrinos [14]. It predicts the half-life for ^{136}Xe in the range $(0.56 - 2.74) \times 10^{25} \text{ yr}$ at 90% CL, for all the corresponding NMEs in [14]. Thus in this case also, the KK claim is compatible with the individual KLZ and EXO bounds, but inconsistent with their combined limit. Similar conclusion holds for the light+heavy neutrino contribution, since the KK claim can be saturated while being consistent with cosmology only by a dominant heavy neutrino contribution; (v) the lower bound is quite sensitive to the

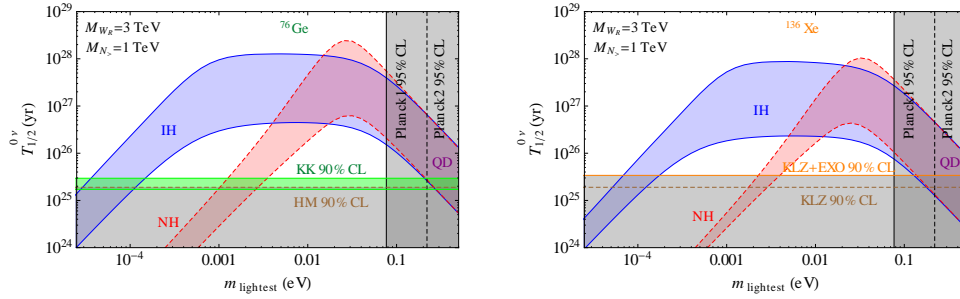


FIG. 2. The light+heavy neutrino contribution as a function of the lightest neutrino mass for both mass orderings and with type-II seesaw dominance. Here $(M_{W_R}, M_{N_>}) = (3, 1)$ TeV. The vertical and horizontal lines are same as in Fig. 1.

RH neutrino and gauge boson masses. For a given W_R mass, increasing (decreasing) the RH neutrino mass will shift the lower bound on the lightest neutrino mass to lower (higher) values, until the heavy neutrino contribution becomes too small to reach the current experimental limit. The trend is similar if we vary the W_R mass, but more pronounced due to the $M_{W_R}^{-4}$ dependence in Eq. (6).

Complementarity with the LHC results – $0\nu\beta\beta$ provides a complementary probe to collider searches for LNV. The correlation between the heavy gauge boson mass and the lightest RH neutrino mass for a TeV-scale LRSM is shown in Fig. 3 for both mass orderings. In the brown (dashed) shaded region, the half-life in Eq. (5) saturates the combined limit from KLZ+EXO [4], whereas the region to its left (right) is excluded (allowed) by this limit. The width of the brown region is due to the variation of the oscillation parameters in their 3σ range [17] and the lightest neutrino mass up to the most stringent upper limit from Planck. We have considered the NMEs for ^{136}Xe corresponding to light and heavy neutrino exchange [14] which yield the smallest $|\langle p^2 \rangle|$, and hence, the strongest limit in Fig. 3. The current LHC exclusion regions [28] are also shown for comparison. We find that (i) for the normal ordering, a part of the parameter space not accessible at the LHC can be constrained (or probed in case of an observation) through $0\nu\beta\beta$, and (ii) for the inverted ordering, it is not possible to exclude any parameter space in the $M_{W_R} - M_{N_<}$ plane from $0\nu\beta\beta$ due to cancellations in m_{ee}^N .

Conclusion – In summary, (i) the positive claim of $0\nu\beta\beta$ in ^{76}Ge is still compatible with the individual ^{136}Xe limits from EXO-200 and KamLAND-Zen due to NME uncertainties, whereas the combined limit excludes this for all but one NME calculations; (ii) the most stringent limit on $\sum m_\nu$ from Planck, in conjunction with the KamLAND-Zen+EXO-200 bound, excludes the possibility of saturating the limit for ^{136}Xe or the claim in ^{76}Ge solely by the canonical light neutrino contribution; (iii) the additional heavy neutrino contribution to $0\nu\beta\beta$ via purely RH currents in the TeV-scale minimal Left-Right extension of the SM can saturate the current experimental bound. For type-II seesaw dominance, it sets a lower

limit on the lightest neutrino mass; (iv) we show for normal mass ordering, $0\nu\beta\beta$ puts additional constraints in the RH gauge boson and heavy neutrino mass plane, complementary to those from LHC.

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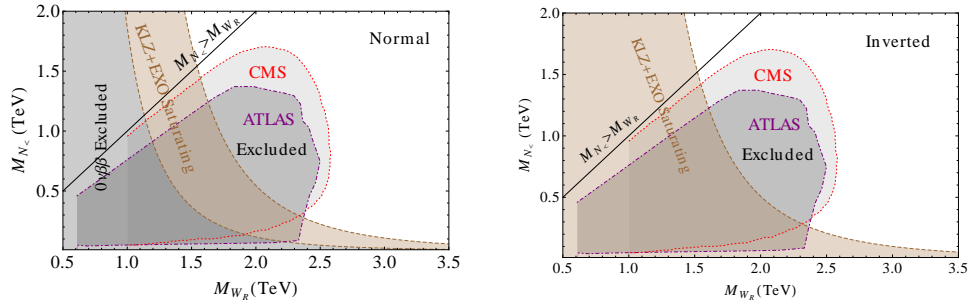


FIG. 3. The $0\nu\beta\beta$ constraints in the M_{W_R} - $M_{N_<}$ plane, along with the direct search limits from CMS and ATLAS. The brown (dashed) region saturates the KLZ+EXO combined limit, and the grey (white) region is excluded (allowed).

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